RESEARCH DEPARTMENT

Investigation of the sound isolation of concrete slab floors

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INVESTIGATION OF THE SOUND ISOLATION OF CONCRETE SLAB FLOORS

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SUMMARY

This report describes experiments designed to explain the difference between the isolation provided by the rubber mountings of studio floors in Broadcasting House Extension and that expected from the design. Methods of improving the isolation by damping the floor vibrations are evaluated.

1. INTRODUCTION

The talks studios in the basement of Broadcasting House Extension were mounted on rubber pads as a protection against noise and vibration from the Bakerloo line which passes very close to the building. The isolation achieved, however, was less than the calculated figures and, although a margin of safety was allowed, the noise level in one studio proved to be higher than the maximum acceptable.

The investigation described in this report was undertaken to find out the cause of this discrepancy.

Some exploratory experiments carried out in Broadcasting House Extension suggested that the mountings themselves were probably satisfactory but, due to resonance effects, high levels of vibration were being produced in the concrete structure which was floated on the rubber mountings.

The studio floors consist of pre-stressed concrete planks supported by rubber mats resting on the structural floor, with three or four inches (approximately 90 mm) of concrete cast on the top. The inner walls are mounted directly on the pre-stressed planks and carry the ceiling. The studio is thus in the form of a box which, apart from its rubber mounting, is independent of the main structure of the building.

The objects of the experiments to be described were

1. To check the efficiency of the rubber mountings themselves.

2. To confirm the presence of resonance effects in concrete slabs, and that these resonance effects were responsible for deterioration in the overall isolation properties of the system.

3. To examine methods of damping the resonances and their effects on the isolation.

In this report the 'isolation' of one point in a system from another denotes the transmission loss between them with particular reference to structure-borne sound. Its definition is therefore similar to that of sound reduction as applied to airborne sound. Used in a general sense 'isolation' applied to structure-borne sounds corresponds to 'insulation' against airborne sounds.

2. EXPERIMENTS WITH CONCRETE SLABS

2.1. Construction of the Slabs

The experimental slabs were not identical in construction to those used in Broadcasting House. Instead of the pre-stressed base, simple reinforced slabs were cast, one of these being 4 inches (101 mm) thick, and the other with a thickness of 3 inches (76 mm). Both slabs had plan dimensions of 8 ft by 6 ft (2·44 m × 1·83 m) which are about one half of typical talks studio dimensions. The slabs were cast in situ on a specially cast concrete foundation in the grounds of Kingswood Warren. During casting the slabs were supported about 6 inches (150mm) above the foundation by square-section concrete sleeper walls which had been cast on the foundation itself. Access was provided under the corners of the slabs for the insertion of hydraulic jacks to allow the slabs to be raised for the placing of isolation mountings between the slab and the supports. The slab could be connected to the foundation by means of five steel bolts screwed through threaded tubes cast in the slab. The experimental arrangement is shown in Fig. 1.

2.2. Preliminary Measurements

2.2.1. Natural Frequencies of Inert Loads on Rubber Mountings

The mountings consist of flat rubber mats 0·40 inches (10 mm) thick with circular studs moulded on both faces giving a total unloaded thickness of 1·12 inches (28·6 mm). The spacing is such that any one stud on either face is centrally disposed in relation to four studs on the other face. Deflection of the mat therefore occurs by bending and shear of the 10 mm rubber sheet between the studs, giving a mounting of suitably low spring rate. The maximum static load is 750 lb/ft^2 (3680 Kg/m^2) and the maximum static deflection 0·12 inches (3·2 mm)

The deflection of one of the mountings under load was first measured. An area of about 1 ft^2 (0·1 m^2) was loaded by weights on a rigid metal plate. The deflection under load was measured with a micrometer at the four corners of the plate.

For a linear spring mounting it may be shown that natural frequency of vibration is given by

$$f_o = \frac{1}{2\pi}\left(\frac{g}{d}\right)^{\frac{1}{2}}$$ where g is the acceleration due to gravity

and d is the static deflection under the load supported.

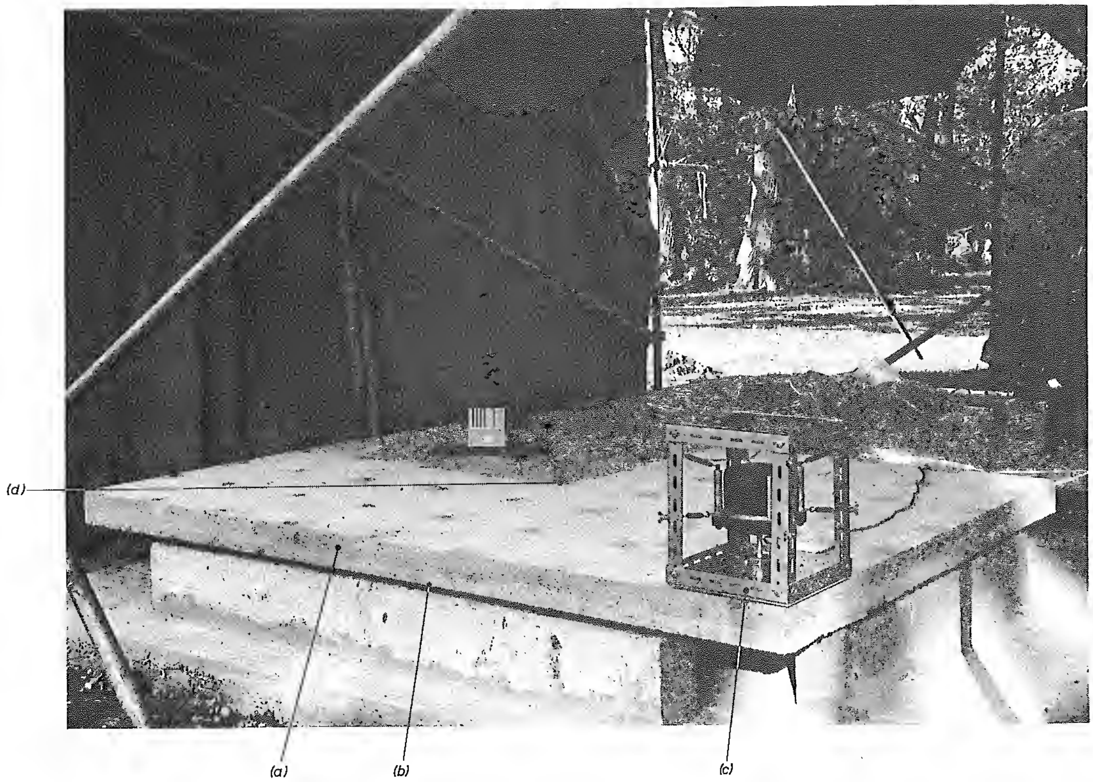

Fig. 1 - Photograph of Experimental slab (a) on rubber mounting (b) showing vibration generator at (c) and accelerometer at (d)

The validity of this formula was first checked on individual mats by loading as for the static tests and measuring the natural frequency of vertical vibration. The measurements were made by mounting a piezo-electric accelerometer on the plate and comparing its output with that of a stable low-frequency oscillator by producing Lissajous figures on an oscilloscope when the system was performing free vibrations.

TABLE 1
Natural frequencies of loads on the rubber mats

LOAD lbs/ft^2	DEFLECTION mm	f_o (CALCULATED) c/s	f_o (MEASURED) c/s
57·5	1·04	15·6	15·5
86·5	1·4	13·5	14·5
115	1·7	12·1	13·5
(4-in slab)	3·2	8·8	8·7
(3-in slab)	2·5	10·0	9·95

The same procedure was used to measure the lowest natural frequency of the two concrete slabs on the mountings. Confirmatory measurements were made by exciting the slab into resonance by means of a Goodman's vibration generator (shown in Fig. 1) driven by the stable oscillator.

Table 1 shows the results of these tests.

The agreement between the last two columns of this table shows that even under the loads of the slabs, the mountings were behaving as substantially linear springs. Non-linearity of the mountings may therefore be excluded as a cause of any disagreement between calculation and measurement of isolation.

2.2.2. Isolation of Inert Loads by Rubber Mountings

Theoretical treatment[1] shows that the transmission loss arising from a simple isolation system is given by

$$\text{Isolation, in dB} = -20 \log \left| \frac{1}{1 - \left(\frac{f}{f_o}\right)^2} \right|$$

where f = frequency, f_o = resonance frequency

This treatment, however, ignores the effect of any damping in the rubber, and as the manufacturer's literature gives no information about the attenuation properties, it was necessary to determine them by experiment.

The rubber mounting was laid on a paving slab acting as a driving platform which was in turn laid on a layer of cork resting on a solid floor. The top of the mounting was initially loaded with weights totalling 116 lb (53 Kg), resting on a Thermalite block. To eliminate unwanted resonances in the system it was later found necessary to dispense with the Thermalite block and reduce the area of the mounting to fit a simple solid 56 lb (25 Kg) iron weight.

Measurements were made by exciting the driving slab by means of a vibration generator and comparing the vibration levels in the driving slab with those in the iron weight.

The results are given in Fig. 2, curve (*a*).

The crosses at the lower end of the curve correspond to readings at small intervals of frequency using a low-frequency pure-tone oscillator. The readings above 100 c/s (circles) were at one-third octave intervals using a warble-tone oscillator, while the transitional points (squares) represent mean values from both types of signal. Curve 2(*b*) is the isolation calculated from the formula given above, assuming f_o = 10 c/s, the frequency calculated from the static deflection. The measured curve (*a*) shows a resonance at a higher frequency (13 c/s). The discrepancy between this and the calculated resonance frequency may be a consequence of the small area of the mat and the resulting departure from its designed mode of deflection.

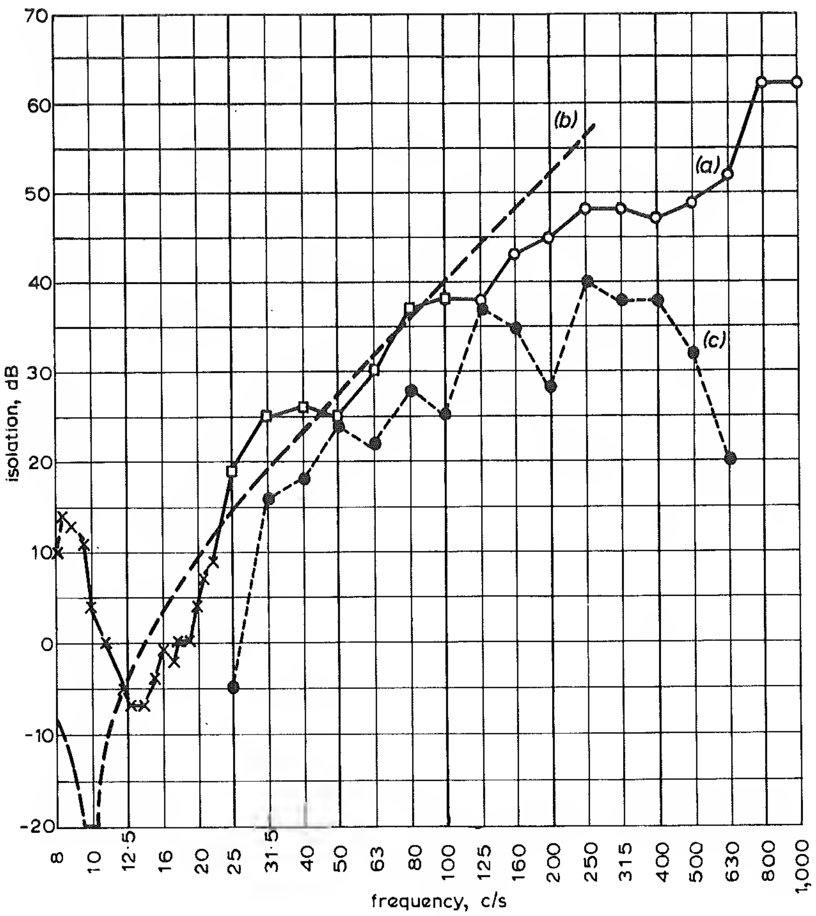

Fig. 2 - Isolation of Inert Weight by Rubber Mats
(a) Measured Curve (Final) *(b)* Calculated Curve
(c) Measured Curve (Initial Arrangement of Load)

Curve 2(*c*) shows the measured isolation with the original arrangement incorporating a larger driving slab and a Thermalite block carrying weights. The reduction of isolation due to unwanted resonances can be clearly seen.

The isolation shown by curve (*a*) is great enough to indicate that the poor performance of the floated floors was not due to any feature of the rubber mountings

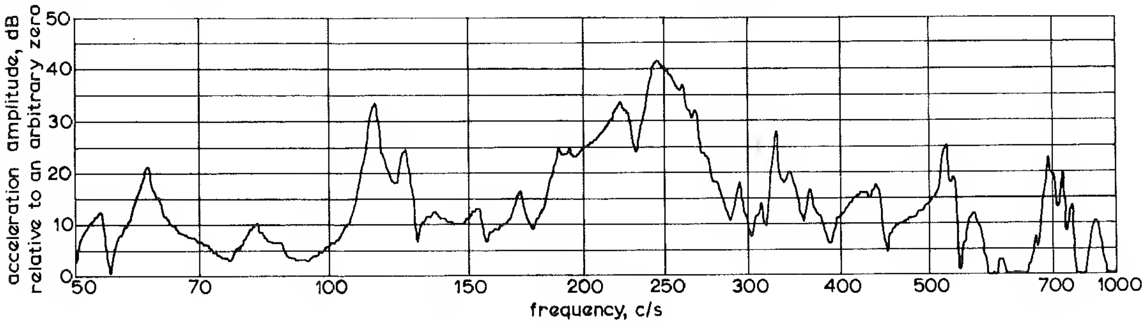

Fig. 3 - Typical steady-state record of 4-inch concrete slab on rubber mats

themselves. The deviation at high frequencies from the calculated curve may be due to the damping in the rubber mat or to airborne sound transmission. It is not however serious enough to warrant further elucidation.

2.3. Steady-state Measurements

Steady-state records were produced by exciting the slab with a vibration generator fed with gliding pure tone and recording the output of the accelerometer on a Bruel and Kjaer level recorder. Both vibration generator and accelerometer were placed in turn at a number of positions on the slab and a typical record is shown in Fig. 3.

The frequency range explored was limited by acoustic and electrical noise to that from 30 c/s to 1 kc/s. There were a large number of resonance peaks inside this range, their frequencies being influenced by the positions of both accelerometer and the vibration generator. In a typical experiment on the thicker slab the lowest peak measured occurred at 48 c/s and the highest at about 710 c/s; other peaks may have been present at higher frequencies but were masked by noise. For the purpose of comparison with later conditions the resonances were divided into 'major' and 'minor' resonance peaks, the former being greater than 10 dB and the latter between 5 and 10 dB. In addition to this classification the amplitudes of the 'major' peaks were also recorded.

In the experimental condition referred to above there were four 'minor' peaks and thirteen 'major' peaks, the average amplitude of the latter being 18 dB. An approximate determination of the average Q factor gave a value of 83.

Measurements on the 3-inch thick slab gave very similar results, though the main features of the steady-state curve occurred at higher frequencies than in the 4-inch slab. There were 12 major peaks below 1 kc/s with an average height of 14 dB.

Fig. 4 shows vibration level contours in the thicker slab at two different frequencies, both corresponding to major resonances. In each case the slab was excited continuously by the vibration generator at one corner and the vibration mapped at the corners of a 6-inch (127 mm) square grid. Two important features will be noted:

1. The great variations in level between points close to each other on the slab and

2. The fact that the presence of the generator causes no noticeable distortion of the contours, indicating that the attenuation across the slab is negligible. This accords with the familiar observation that a single point of high transmission (a 'bridge') connecting a floating floor to the structural floor causes a serious impairment in the isolation of the whole floor from the building.

2.4. Impact Response

A recording was made of the response of the accelerometer in each of several positions to blows on the slab. For this purpose a ball of plasticine dropped on to the slab was found to be a convenient method of excitation as the material itself does not resonate.

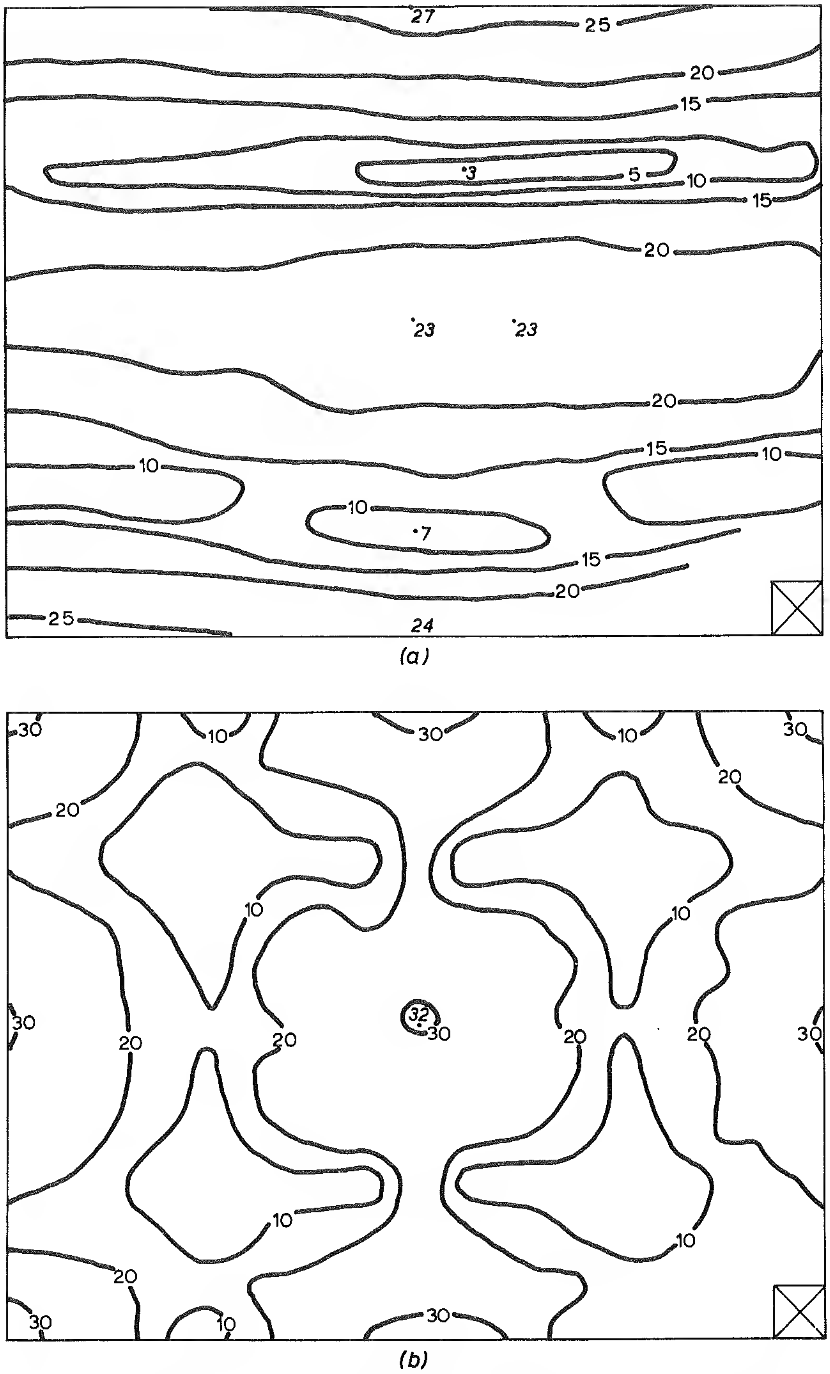

Fig. 4 - Acceleration-amplitude distribution over surface of 4-inch rubber-mounted slab

(a) 112 c/s *(b)* 250 c/s

(Figures represent dB above arbitrary zero)

The recordings were subsequently analysed using octave and one-third octave filters with a high speed level recorder and Peak Programme Meter as indicating instruments. The decay times of the filtered components were also measured using reverberation time standards in which the times quoted refer to the time taken to decay to a value 60 dB below the initial level.

The acceleration amplitudes obtained from a one-third octave analysis of the blows showed variations in level of some 15 dB at frequencies below 400 cycles but provided almost constant values above this frequency up to 8 Kc/s. Reverberation times varied from over 3 seconds in the octave centred on 63 c/s to 0·3 seconds for that at 500 c/s.

2.5. Measurements of Sound Isolation from Structure-borne Sound

The method adopted in principle for the measurement of the isolation of the slab as a whole from the ground beneath was to set the ground into vibration and compare the acceleration levels measured on the slab and in the ground respectively. To obtain a sufficiently uniform vibration under the slab, the source should be placed at a distance large in comparison with the dimensions on the slab.

Listening tests showed that for excitation of the ground by falling weights or a vibration generator much of the slab vibration was due to airborne sound. This observation was confirmed by replacing the source by a loudspeaker radiating the recorded airborne sound adjusted to the same pressure level. It was found that ground vibration near the slab for distant sources had a negligible influence on the excitation of the slab. Measurements were made of the sensitivity of the slab to airborne sound by comparing the acceleration of the slab surface with the sound pressure produced just above the surface by a distant loudspeaker. The method has been described by one of the authors.[2] The results showed that the sensitivity is 15 dB greater at resonance frequencies than that to be expected by a non-resonant slab of the same mass.

The arrangement finally adopted for measuring the isolation from groundborne sound was to mount the vibration generator, enclosed in a heavy box, near to the slab and to compare the r.m.s. averages of the vibration levels on the foundations and on the slab. The isolation measured in this manner rose from 5 dB to 15 dB between 80 c/s and 1 kc/s.

2.6. Comparison of Rubber and Cork Mountings

The investigation was carried further by using the thin slab to compare the efficiency of cork and rubber mountings. The cork was that specified for the load, and so could be considered as a direct replacement for the rubber mats. Due to its higher stiffness it would however be expected to provide less isolation.

For this purpose a measurement of reverse isolation was made, in which the levels due to blows on the slab were compared at several points on the slab and on the foundation. Hammer blows were used, with a resilient plate interposed to increase the energy at low frequencies which is otherwise deficient. The difference in level was a measure of the attenuation between the slab and the foundation, bearing in mind that the foundation was directly connected with the earth. Three conditions were examined:

1. The slab was allowed to rest directly on its concrete supports.
2. Rubber mats were inserted as before.
3. The rubber was replaced with an equivalent area of cork.

In Table 2 are listed the values of attenuation achieved in the three conditions. The improvement in attenuation obtained by insertion of the resilient material represents the insertion loss due to the cork and rubber respectively. These values are listed in octave bands in the final columns of the table. It will be seen that the insertion loss due to rubber was of the order of 20 to 25 dB greater than that due to cork.

TABLE 2

Insertion Loss due to Rubber and Cork Mountings

ATTENUATION, THREE-INCH SLAB TO FOUNDATION				INSERTION LOSS	
MID-FREQ. OF OCTAVE BAND	DIRECT	RUBBER	CORK	RUBBER	CORK
63 c/s	16dB	47dB	20dB	31dB	4dB
125 c/s	22	55	30	33	8
250 c/s	19	50	31	31	12
500 c/s	27	54	28	27	1
1 Kc/s	28	49	44	21	16
Flat 40 c/s to 2 Kc/s	24	52	29	28	5

3. THE EFFECTS OF DAMPING

3.1. General

The measurements described above refer to a simple reinforced concrete slab mounted on rubber, and were intended to establish the main characteristics of such a system. Simple experiments on the effects of reducing the magnitudes of resonance effects were next carried out.

For this purpose dry sand, 2 in (50 mm) in depth, was laid on the surface of the slab, shuttering being provided to allow a uniform level to be maintained to the edge of the slab. A layer of 2 ft × 2 ft × 2 in (610 × 610 × 50 mm) concrete paving stones was then arranged on top of the sand. This treatment was intended to provide a measure of frictional resistance without adding any appreciable rigidity to the slab.

3.2. Steady-state Measurements with Sand Layers

Steady-state curves were obtained and analysed as described for the undamped slab. At the generator position the damping layers were penetrated by solid wooden

supports to ensure that the excitation force was independent of the presence of the damping. The results, given in Table 3 below show a significant reduction in the number of major peaks when the damping was added, though no other change.

TABLE 3

Resonance Maxima from steady-state records - Four-inch slab

UNTREATED			TREATED		
FREQUENCY (C/S)		RELATIVE AMPLITUDE (dB)	FREQUENCY (C/S)		RELATIVE AMPLITUDE (dB)
MINOR	MAJOR	MAJOR	MINOR	MAJOR	MAJOR
	48	26	46	38	23
	55	15		-	
80	-	-		80	22
110	-	-	110	-	
	120	28			
	149	25			
	170	22		165	15
	230	18			
	245	17		270	20
	300	12			
330	-				
	350	17			
	430	11			
	460	10			
	530	13		550	15
	600	23			
710			700		
			880		
Totals 4	13		4	5	
Means		18			19

The vibration level for a given power input was also greatly reduced, as shown in Table 4.

TABLE 4

Steady-state - Comparative Acceleration Amplitudes of the 4-inch Slab for same Vibration Energy Input (dB Relative to an Arbitrary Zero)

	PEAK LEVEL dB	AVERAGE OF 5 HIGH LEVEL PEAKS dB	AVERAGE (SAMPLED) dB
Untreated	62	58	36
Sand only	57	56	38
Sand and Paving Stones	47	44	29

In this table, the first column shows the level of the highest peak in the steady-state curve, the second is the mean of the five highest peaks while the last column is the average level obtained by sampling at equal intervals of frequency from 50 c/s to 1 Kc/s.

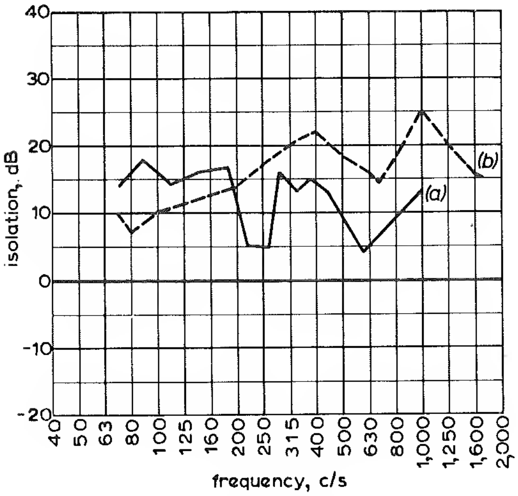

Fig. 5 - Isolation of rubber-mounted 4-inch concrete slab from foundation

(*a*) Undamped
(*b*) Damped with sand and paving slabs

3.3. Isolation Measurements with Treated Slab

Fig. 5 compares the isolation of the slab from its foundations measured as described in Section 2.5 above, with and without the sand treatment. Curve (*a*) is for the undamped slab, curve (*b*) for the damped slab. There is an improvement averaging 10 dB above 200 c/s due to the treatment; the reduction below 200 c/s has not been explained.

4. DEVELOPMENT OF A PRACTICAL DAMPING TREATMENT

4.1. Introduction

A series of experiments was started to investigate practical methods of reducing resonance effects in concrete floors. Two pre-stressed concrete planks 8 ft × 13 in. × 2 in. (2·44 m × 330 mm × 50 mm) were obtained, similar to those used in B.H. Extension and in the Echo Rooms at Television Centre. One of the advantages of this type of construction was that it provided models of convenient area for experiment, while at the same time having the characteristics of a full-scale construction. Because of their smaller size it was possible to mount the experiment inside a building and maintain a constant temperature as a precaution against possible variation in properties of damping materials with temperature. A temperature close to that which would be found in a studio building was maintained throughout the measurements. The experimental arrangement is shown in Fig. 6.

4.2. Experimental Techniques

Measurements were made by the methods described in Section 2 of the steady state behaviour, the reverberation time, the isolation and the sensitivity to airborne sound. For the isolation measurements, it was found that the floor of the building was too rigid for satisfactory excitation by the methods of Section 2 and airborne sound level was too high. The planks were therefore erected outdoors on a resiliently mounted base.

4.3. Experimental Conditions

Some preliminary experiments were done on one plank to find a suitable damping material. It was required of this material that it should withstand studio floor loadings, be suitable for application inside a studio and should be reasonably

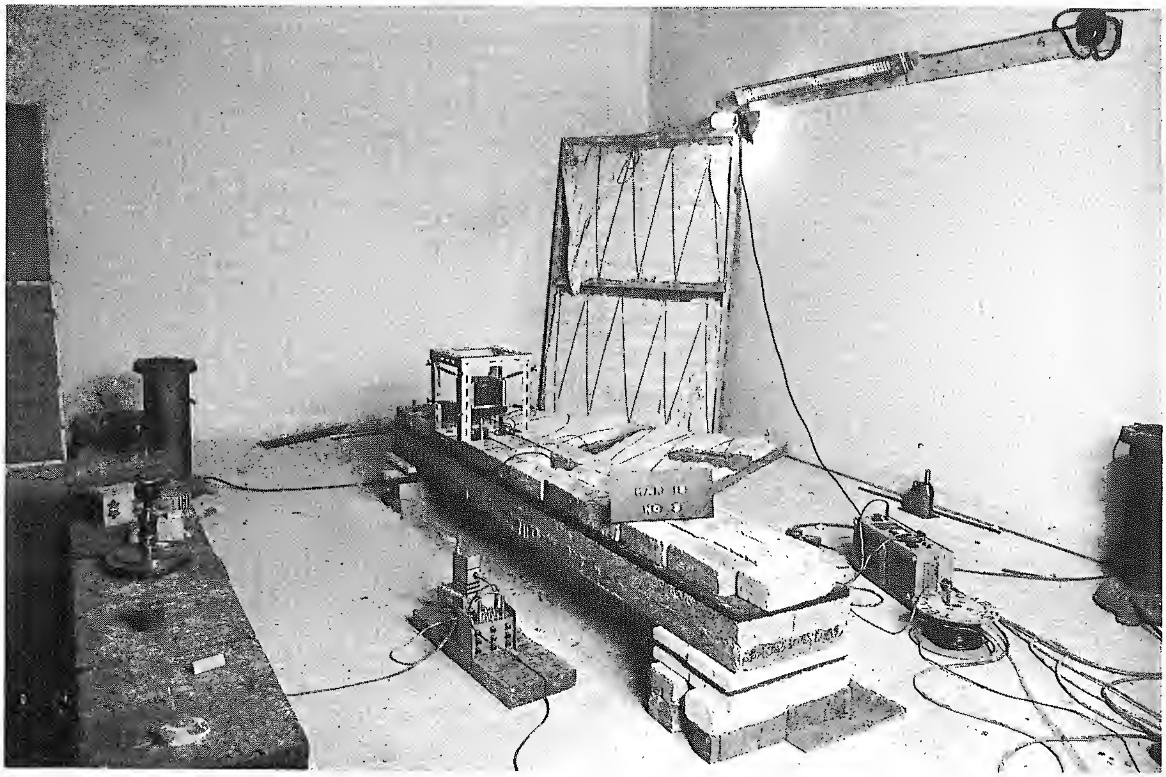

Fig. 6. - Photograph of pre-stressed concrete planks mounted on rubber pads

cheap. Asphalt or bitumen had been suggested as a material[3] but used on its own it requires to be heated in order to apply it. It could, however, be used as a binding material for sand or gravel, allowing the latter to experience some movement amongst its particles while having a reasonable rigidity. The material eventually used was a mixture of fillers, portland cement and an emulsion of asphalt in water, which could be laid cold. It was essentially concrete with most of the water replaced by the asphalt emulsion and the amount of cement about half that in ordinary concrete. The mixture was found to be sufficiently stable to allow removal of the shuttering within 24 hours, but required one or two days more for complete drying out.

The second plank was then covered with a 2 in. (50 mm) layer of concrete to simulate the normal construction of a studio floor. This is referred to below as the basic construction.

Subsequently each of the following treatments was applied and tested separately:

1 in. (25 mm) asphalt concrete
1 in. (25 mm) asphalt concrete and one 3 in. (76 mm) layer of bricks
2 in. (50 mm) asphalt concrete
2 in. (50 mm) asphalt concrete and one 3 in. (76 mm) layer of bricks

4.4. Steady State Measurements

Steady state records were obtained by the method described for the reinforced concrete slabs in Section 2.3. The numbers of major and minor peaks and the average Q associated with the major peaks is shown in Table 5.

TABLE 5

Analysis of steady state response of plank

	NUMBERS OF PEAKS MAJOR	NUMBERS OF PEAKS MINOR	AVERAGE Q
(i) Basic construction	3	7	117
(ii) One-inch asphalt concrete	2	5	37
(iii) One-inch asphalt concrete loaded with bricks	2	2	21
(iv) Two-inch asphalt concrete	1	4	16
(v) Two-inch asphalt concrete loaded with bricks	1	3	16

It will be seen that the number of major and minor peaks is reduced by the first application of asphalt concrete and further reduced by the addition of the bricks. The second inch of asphalt was a slight improvement over the first inch, but subsequent loading with bricks produced no significant change. The Q-values confirm these results, showing a reduction with each stage except the last.

As further confirmation, the acceleration amplitude of the plank was measured in each of the five conditions, the force applied by the generator being held constant.

The acceleration amplitudes at constant force input were compared for different treatments. Three figures were derived for each condition: the maximum peak height, the average height of the highest five peaks and the average level sampled at equal intervals from 100 c/s to 1 Kc/s.

The effect of the asphalt treatment was greatest on the highest peaks which were reduced by 25 dB in the third condition compared with the basic condition. The mean of the highest five peaks was similarly reduced by 17 dB, but the average response between 100 c/s and 1 Kc/s was not significantly affected. Here, again, no advantage was found in adding a second layer of the asphalt mixture, the best condition being with one inch of asphalt and a layer of bricks.

4.5. Impact Response

The excitation of the plank by blows was studied by the methods described in Section 2.4. Analysis of the plank vibrations due to a constant impact showed an average reduction of over 25 dB with the most effective treatment (one inch of asphalt loaded with bricks) as compared with the untreated plank. The greatest reductions were at the frequencies of resonance. The decay time of the plank showed a tenfold reduction with treatment, and a smoothing of the reverberation time/frequency curve.

Measurements of the reverberation time were made using one of Acoustics Section's oscilloscopes and logarithmic amplifiers for the longer reverberation times and it was found convenient to replay the tape at half speed in some cases to overcome the limitation imposed by the writing speed of the logarithmic amplifier. As treatment proceeded and the reverberation time became very short, it was found necessary to use an instantaneous logarithmic amplifier instead of the rectifying type normally used. The device used was limited to about 30 dB useful range, but under the signal-to-noise conditions encountered this was quite adequate.

4.6. Isolation Measurements

Measurements of isolation were confined to the plank treated with two inches (50 mm) of asphalt concrete. Fig. 7 shows the results of these measurements obtained by the method of Section 2.2. Both impulsive and continuous excitation of the lower slab were used, giving very similar results. The mean isolation shown by the graph is 34 dB between 100 c/s and 1 Kc/s.

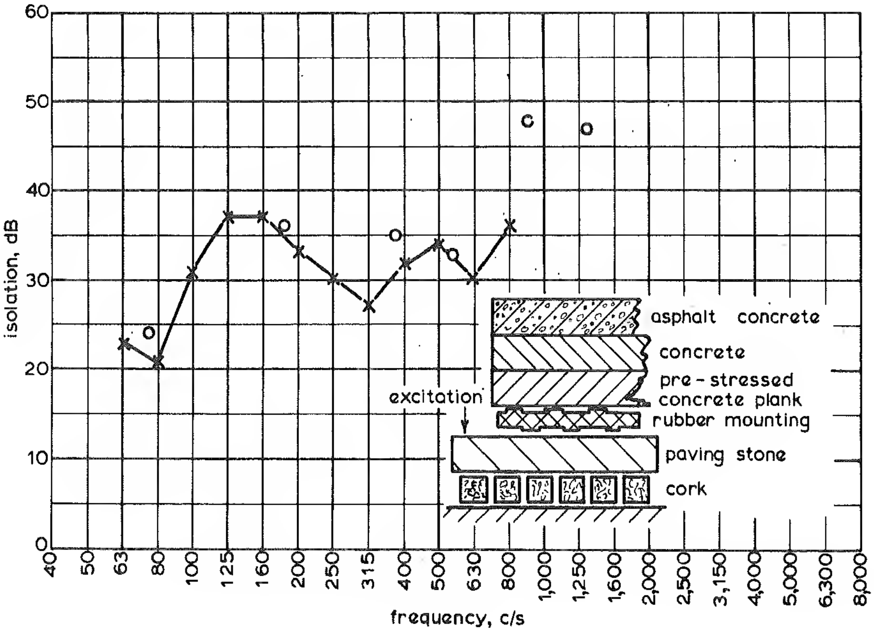

Fig. 7 - Isolation of pre-stressed concrete slabs from foundation

× Impulsive excitation o Pure-tone excitation

5. EFFECTS OF POINT-LOADING OF THE ENDS OF THE PLANKS

In the Television Centre echo rooms, each plank spans the width of the room. Its ends are mounted on a peripheral strip of rubber mat and carry the walls. In Broadcasting House Extension Studios two planks are required to span the width, the joints being carried on a central strip of mat. Thus there is heavy loading on both ends of the Television Centre planks but on one end only in Broadcasting House Extension.

The effect of these end loadings on the behaviour of the planks was studied, the plank having one inch of asphalt over the concrete screed. The results of impact response tests showed no clear changes in the general behaviour of the plank due to the additional loading, though the lowest resonance frequency was reduced.

There was no change in the resonance frequencies or the damping of the plank when steel rollers were substituted for the rubber mountings.

6. CONCLUSIONS

1. The difference between the actual and expected isolation provided for the Broadcasting House Extension studios is not due to faulty behaviour of the rubber mountings.

2. Resonances in the floor structure amplify airborne and structure borne vibrations and thereby reduce the effective isolation.

3. Damping of the structural floor resonances can be effected by the application of a layer of asphalt concrete to the surface of the floor.

4. Improved damping is obtained by loading the damping layer with a layer of bricks.

5. One method of construction might be to interpose the damping layer between the pre-stressed concrete planks and the concrete screed which together form the complete floor structure.

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